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Structural Fire Engineering Study on Unprotected Long Span Steel Trusses

H. C. HO [a]*, K. F. CHUNG [a], Y. WONG [b]

[a] *Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong SAR.*
[b] *Arup Fire, Ove Arup & Partners Hong Kong Limited, Hong Kong SAR.*

Abstract

This paper presents a structural fire engineering study on the thermal and structural performance of a 33.6 x 33.6 m space truss comprising of 8 longitudinal and 4 transverse unprotected steel trusses. Details of the finite element modeling are thoroughly described, and both non-linear thermal and structural analyses are presented to illustrate the general modelling procedures. Moreover, a number of general principles on data analyses and interpretation of the numerical results are discussed whilst specific failure criteria for the long span trusses in terms of various stress and deformation levels in members and in supports are also proposed. It is envisaged that the experiences gained from the present study will contribute to the wide application of structural fire engineering study in steel building structures.

Keywords: Structural fire engineering, Unprotected steel, Fire scenario, Finite element modelling

1. Introduction

In structural fire engineering studies, it is widely recognized that performance-based approaches often provide great advantages over prescriptive approaches as rational engineering methods are adopted to assess overall structural safety of building structures at elevated temperatures. However, it is usually very difficult not only in establishing suitable numerical models to simulate detailed behaviour of the structure under fire, but also in establishing the key parameters for meaningful analyses as well as in interpreting the numerical results in a holistic manner. Hence, many modern fire codes recommend the use of either a prescriptive approach or a combination of both prescriptive and performance-based approaches. In general, the most important requirement for a successful implementation of a performance-based

* Corresponding author
E-mail address: cekchung@polyu.edu.hk

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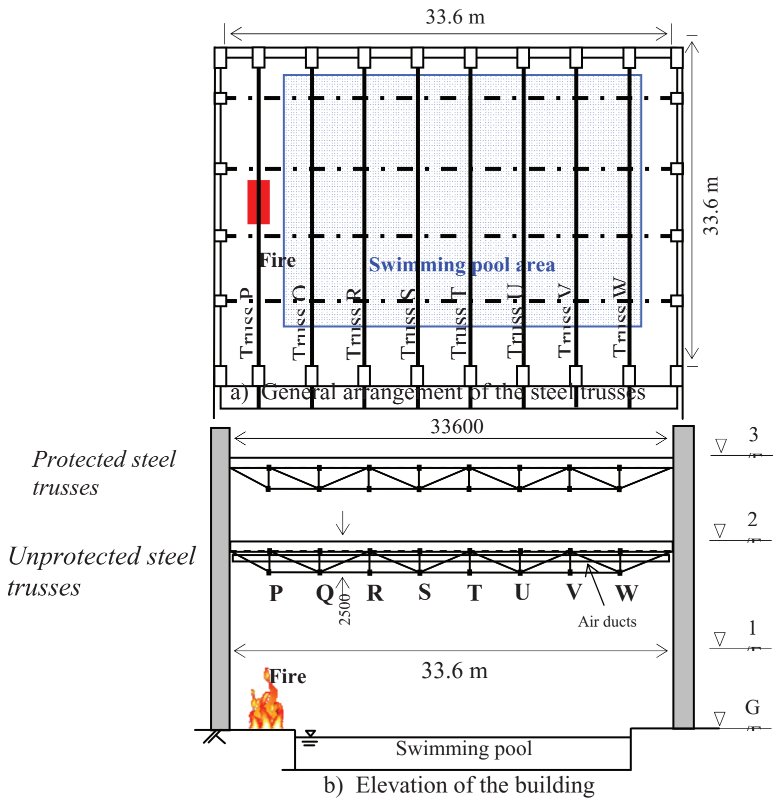
approach of structural fire engineering in a building is a realistic assessment of its structural responses under specific fire exposures (Chung & Wang, 2006).

At present, there is a lack of established modelling procedures on thermal and structural analyses of a building structure together with the general principles on data analyses and interpretation of the numerical results. Moreover, it is also necessary to define and formulate specific failure criteria for the structure under consideration.

This paper presents a structural fire engineering study on the thermal and structural performance of a 33.6 x 33.6 m space truss comprising of 8 longitudinal and 4 transverse unprotected steel trusses. Details of the finite element modeling are thoroughly described, and both non-linear thermal and structural analyses are presented to illustrate the general modelling procedures. Moreover, a number of general principles on data analyses and interpretation of the numerical results are discussed, and specific failure criteria for the long span trusses in terms of various stress and deformation levels in members and in supports are also proposed.

In the present study, the building under consideration is an indoor recreation centre with a swimming pool at the ground floor, and it is mainly constructed of reinforced concrete with long span steel trusses at both 2/F and 3/F, as shown in Figure 1.



a) General arrangement of the steel trusses

b) Elevation of the building

Figure 1: General layout of the building

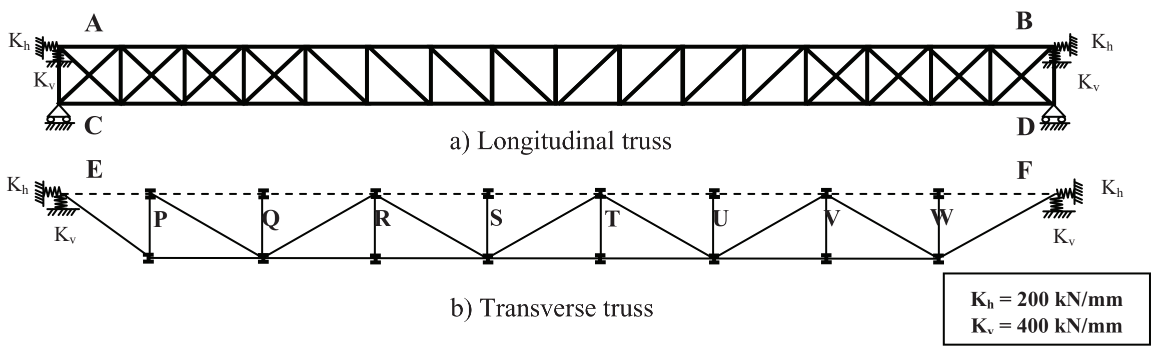
It should be noted that:

a) As the total design loads for fire at both 2/F and 3/F are found to be 17.5 kPa (which is considered to be fairly large), it is common practice to provide fire protection systems to the supporting steel trusses.

b) However, there is no floor slab in the swimming pool area at 1/F, and a large headroom exists directly over the swimming pool area. Hence, extensive temporary works with double storey heights are needed if fire protection systems are provided to the supporting steel trusses at 2/F; this is very expensive and time consuming.

c) It is reckoned that the supporting steel trusses at 2/F may be unprotected owing to the presence of large volume underneath whereas the risk of fire inside the swimming pool area is extremely low. Hence, a structural fire engineering study on the supporting steel trusses at 2/F to is carried out to verify their structural adequacy at fire. It should be noted that the steel trusses supporting the floor slab at 3/F are fully protected.

Typical member configuration of the steel trusses is illustrated in Figure 2. The top chords in both the longitudinal and the transverse trusses are restrained laterally in the presence of the floor slabs.



Top chord:	UC 305 x 305 x 198 S355	Bottom chord:	UC 305 x 305 x 198 S355
Diagonal and vertical members:	UC 203 x 203 x 71 S355	Linking members:	RSC 180 x 90 x 26 S355

Figure 2: Member configurations of the steel trusses

2. Thermal analyses

In order to evaluate the temperatures of the steel trusses under fire, a computational fluid dynamics simulation software, namely, Fire Dynamics Simulator (or FDS) is employed. The FDS is developed and maintained by the Fire Research division of the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST, 2006)). After much consideration, a credible fire scenario with a fire size of 5 MW and a fire duration of 30 minutes is adopted in the non-linear thermal analysis to evaluate the surface temperatures of the steel trusses. The fire source is located at the ground level underneath the mid-span of Truss P, as shown in Figure 1. It should be noted that the adopted fire size of 5 MW is considered to be extremely large as a fire in the swimming pool, and thus, the fire scenario is extremely conservative. The thermal analyses are carried out at a time step of 1 minute, and the temperatures of the steel members are assumed to be the same as those of the surrounding air for simplicity.

As expected, it is found from the numerical results of the thermal analyses that among all the trusses, Truss P is the hottest, and the temperature distribution history of Truss P over the fire period of 30 minutes are plotted in Figure 3. It should be noted that the maximum temperatures in the steel members are 149 and 190 ^{o}C at the mid-span of the top and the bottom chords respectively 21 minutes after ignition of fire whilst the temperatures of all the members in the other trusses are lower than 50 ^{o}C.

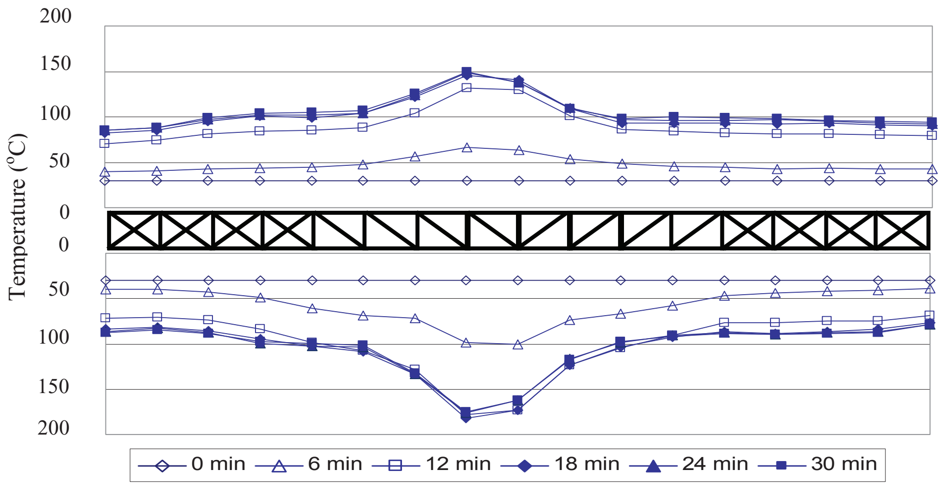
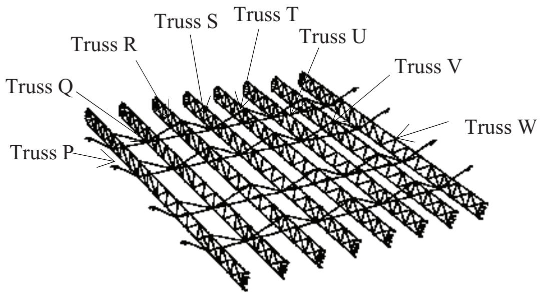


Figure 3: Temperature distribution history of Truss P

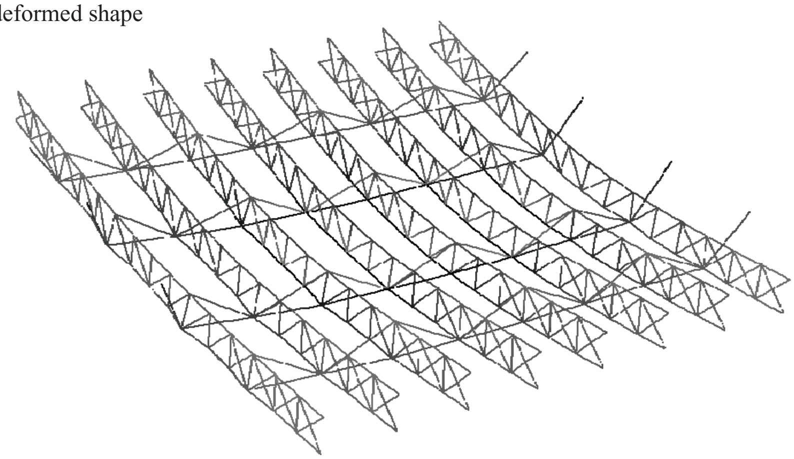
3. Structural Analyses

As the temperatures of most of the steel members obtained from the thermal analyses are considered to be fairly low, when compared to the limiting temperature of 550 ^{o}C, it may be argued that there is little thermal effect onto the steel trusses during fire. However, detailed structural analyses reveal that it is important to examine the long span trusses at elevated temperatures, even in the range of a moderate temperature rise of 200 ^{o}C. Despite small reduction in strength and stiffness, thermal expansion in the long span steel trusses should be examined. More specifically, induced deformations and reaction forces of the steel trusses at supports caused by restrained thermal expansion should be carefully assessed.

In the present study, the general purpose finite element package ABAQUS (Version 6.4) (ABAQUS User's Manual, 2004) is employed, and a total of 8 longitudinal and 4 transverse steel trusses are modelled with two-noded truss elements T3D2T; the finite element model is shown in Figure 2. All the steel trusses are partially restrained at end supports against both vertical and horizontal directions while the top chords in the steel trusses are assumed to be effectively restrained against lateral buckling. The stress-strain curves of the steel sections at elevated temperatures recommended in Eurocodes 3 and 4: Parts 1.2 (BSI, 2005) are adopted in the analyses together with the corresponding non-linear thermal expansion coefficient. The Newton-Raphson iterative solution procedures are employed in order to achieve force equilibrium and deformation compatibility at each time step. Figure 4 illustrates the typical deformed trusses at elevated temperatures.



a) Undeformed shape



b) Deformed shape under design load

Figure 4:Finite element model of the steel trusses

Moroever, the following failure criteria of the steel trusses are proposed:

- Member failure

A member is considered to be failed when:

i. $\sigma > r_\theta fy$

where σ is the applied stress of the member; r_θ is the strength reduction factor of steel at temperature θ, and f_y is the yield strength of steel at room temperature.

ii. $\varepsilon > \varepsilon_{L,\theta}$

where ε is the total strain of the member at temperature θ; $\varepsilon_{L,\theta}$ is the limiting strain of steel at temperature θ.

Both r_θ and $\varepsilon_{L,\theta}$ may be readily obtained from Eurocode 3: Part 1.2.

It should be noted that the applied stresses in all the members in the steel trusses are found to be smaller than the residual strengths of steel at the corresponding temperatures. Moreover, the maximum member strain among all the members in the steel trusses is found to be merely 0.85 %. Hence, there is no member failure.

- System failure

As load re-distribution is highly efficient within the steel trusses owing to their effective structural forms, any member failure does not necessarily signify a system failure. Thus, it is appropriate to assess system failure of the steel trusses against a global deflection limit of span/20, i.e. 33600 / 20 or 1680 mm.

The mid-span deflections of all the longitudinal steel trusses during the entire fire period are plotted in the same graph of Figure 5 for direct comparison. It is shown that although Truss P is the hottest among all the trusses, its mid-span deflection is found to be the smallest as it is well supported through 4 diagonal members to an adjacent wall. Instead, Truss S is found to deflect the most, with a mid-span deflection at 140.2 mm, 11 minutes after the ignition of fire.

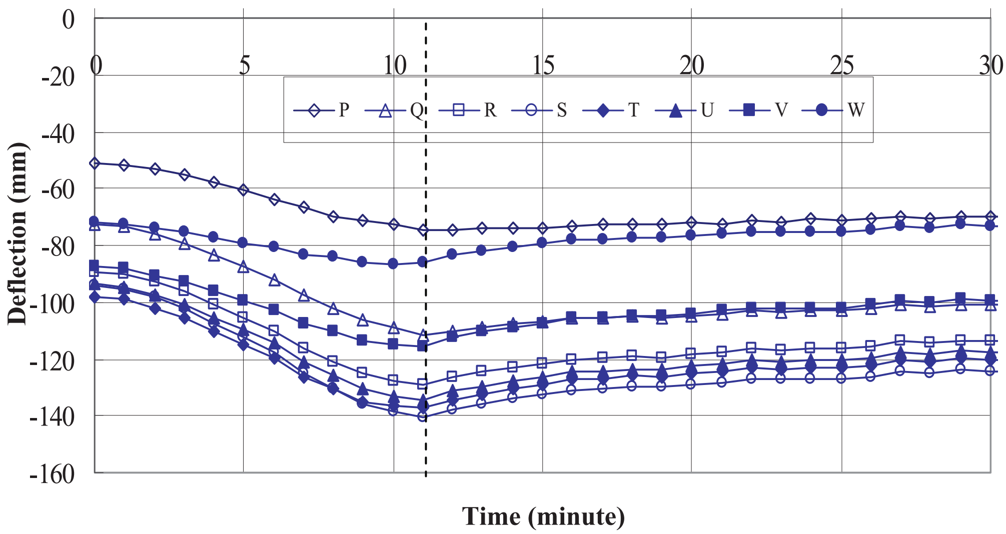


Figure 5: Deformation histories of the steel trusses

Table 1 summarizes the mid-span deflections of Trusses P and S at various times after ignition of fire. As the mid-span deflection of Truss S at room temperature is 94.1 mm, and hence, the additonal deflection due to fire is merely 46.1 mm, which is significantly smaller than the deflection limit. Consequently, there is no system failure.

Table 1: Mid-span deflections of Trusses P and S

	Mid-span deflection (mm)		
	At time = 0 minute	*At time = 11 minutes*	*At time = 30 minutes*
Truss P	51.2	74.0	70.1
Truss S	94.1	140.2	124.3

Moreover, detailed examination on the numerical results of the structural analyses reveal that it is important to assess the effect of thermal expansion in the long span steel trusses, and both induced deformations and reaction forces of the steel trusses at supports caused by restrained thermal expansion, as shown in Table 2, should be carefully assessed as follows:

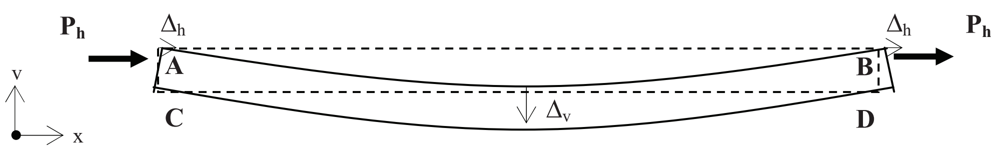
- For Truss P, the horizontal reaction force at Support A is increased significantly from -699 kN (tensile force) at room temperature to 1544 kN (compressive force). Hence, a compressive force with a magnitude of 2243 kN is induced at the support due to restrained thermal expansion, as shown in Figure 6.

- For Truss S, the horizontal reaction force at Support A is reduced significantly from -1294 kN (tensile force) at room temperature to 234 kN (compressive force). Hence, a compressive force with a magnitude of 1528 kN is induced at the support due to restrained thermal expansion, as shown in Figure 6.

Table 2 Summary of movements and reaction forces at supports

Truss P	*At time = 0 minute*		*At time = 30 minutes*	
Support	Δ_h (mm)	P_h (kN)	Δ_h (mm)	P_h (kN)
A	3.5	-699	-7.7	1544
B	-3.5	699	7.7	-1544
C	-6.7	0	-23.4	0
D	6.7	0	-22.9	0

Truss S	*At time = 0 minute*		*At time = 30 minutes*	
Support	Δ_h (mm)	P_h (kN)	Δ_h (mm)	P_h (kN)
A	6.4	-1294	-1.2	234
B	-6.4	1294	1.2	-234
C	-12.3	0	26.7	0
D	12.3	0	-26.7	0



Hence, from the structural fire engineering study, large variations in the forces and the movements of the supports during heating up of the steel trusses are identified. It is important to ensure that all the supports and the connections of the steel trusses are able to resist the large reaction forces and to accommodate the large support movements during the entire fire period. In general, the magnitudes of those forces induced by restrained thermal expansion are directly related to the restraining stiffnesses at the supports as permitted by their constructional details.

It should be noted that these induced compressive forces are of the same order of those internal forces caused by the dead and the imposed loads. Moreover, it is possible to reduce the induced compressive forces, if needed, by adopting supports with low restraining stiffnesses at the expenses of increased mid-span deflections of the steel trusses.

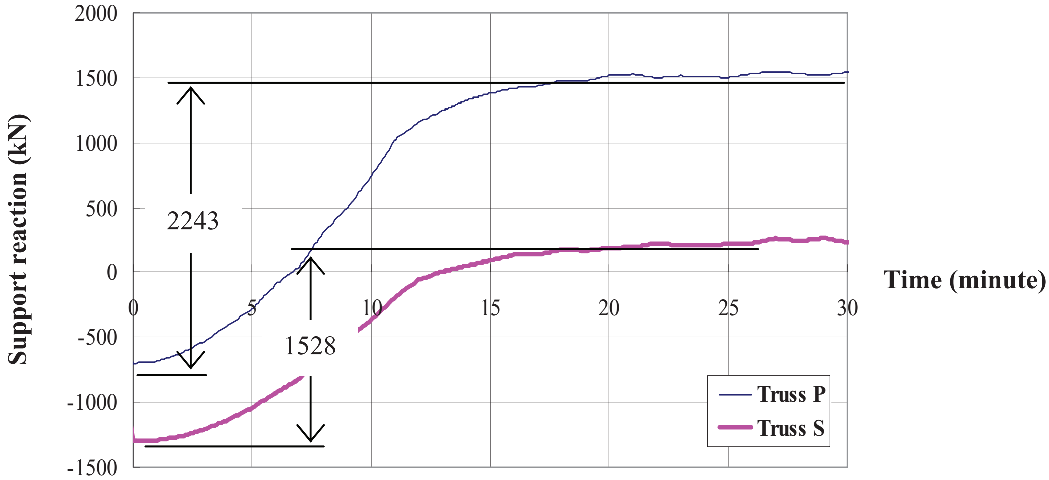


Figure 6: Force reversal at supports

4. Conclusions

This paper presents a structural fire engineering study on the thermal and structural performance of a 33.6 x 33.6 m space truss comprising of 8 longitudinal and 4 transverse unprotected steel trusses. It is found that the structural responses of the steel trusses under a credible and yet conservative fire scenario, i.e. a fire size of 5 MW with a fire period of 30 minutes, are highly satisfactory in terms of stress and strain levels of the members as well as global deformation of the steel trusses. It is verified that no fire protection system to the steel trusses is required. However, it is important to assess the effect of restrained thermal expansion in the steel trusses even under a moderate temperature rise in the range of 200 ^{o}C. Based on the results of the advanced finite element modeling, it is found that large compressive forces are induced at the supports together with significant support movements, causing force reversal in the chord members. Consequently, it is necessary to check all the steel members and the connections of the steel trusses, and about 30% of the connections are re-designed. Hence, it is essential to carry out advanced structural fire engineering studies to assess the structural behaviour of unprotected steel structures at elevated temperatures. The analyses will provide data on the structural behaviour of the steel structures as well as their supports for proper design, and these are normally not available in conventional structural analysis and design.

Reference

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